

Interactions and mergers at higher redshift

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Abstract.

In models of hierarchical structure formation, interactions and mergers at high redshift play a key role in the formation and evolution of galaxies. Numerical modeling and observations of nearby systems explore the detailed physics of galaxy interactions, but applying these results to the high redshift universe remains complicated. Evolution in the properties of galaxies over cosmic history may lead to differences in interaction-induced star formation as a function of redshift. High redshift interacting galaxies may be more prone to extreme, disk-wide starburst activity than are low redshift systems. Also, while activity in nearby clusters seems to be largely diminished, at higher redshift we observe galaxies falling into clusters for the first time. A variety of processes, including interactions and mergers, can drive strong evolution in cluster galaxies at higher redshift.

1. Lessons from the Nearby Universe

Most of our detailed knowledge of the effects interactions have on galaxies comes from studies grounded in the local universe. Well-studied samples of interacting galaxies such as the Toomre (1977) sequence extend only out to $\sim 10,000$ km/s, and so much spatial information is lost at redshifts greater than a few tenths that we can only rely on statistical studies of interactions at higher redshift. Dynamical models, which have illuminated many of the physical processes involved during galaxy collisions, rely heavily on galaxy models constructed to resemble nearby galaxies in terms of their structural and kinematic properties. Whether such models accurately portray interacting galaxies at high redshift is unclear – structural differences between high and low redshift galaxies may translate to substantial differences in the response to an interaction.

Nonetheless, these dynamical models allow us to view the basic evolution of a merging encounter (Figure 1, from Mihos & Hernquist 1996 [MH96]). Shortly after the initial passage, the galaxies become strongly distorted, with disk self-gravity amplifying the perturbation into strong spiral arms or central bars. As the galaxies separate, dynamical friction between the dark halos slows the galaxies on their orbit, causing them to fall back and merge together. The violent relaxation accompanying the merger destroys the disks and results in the creation of an elliptical-like remnant. During the interaction and ensuing merger, a large fraction of the galaxies' ISM is compressed and driven inwards due largely to gravitational torques during the encounter. This compression and inflow presumably leads to strong starburst and/or AGN activity during the encounter.

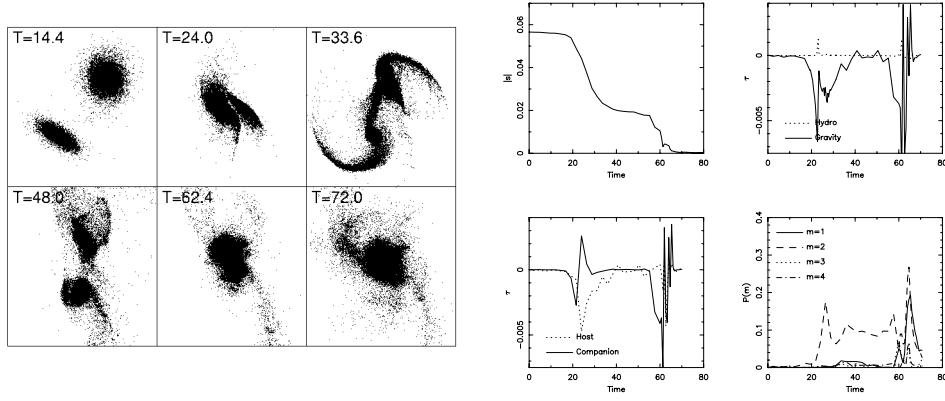


Figure 1. Left: Evolution of an equal mass merger, from MH96. Time is given in model units; the sequence covers approximately 750 Myr. Right: Evolution of the inflowing gas. The subpanels show (top left) the angular momentum of the gas, (top right) the gravitational and hydrodynamic torques acting on the gas, (bottom left) the gravitational torques from the host and companion galaxies respectively, and (bottom right) the growth of nonaxisymmetric modes in the stellar disk.

The triggering of enhanced star formation by interactions is borne out in the observational record, but the effects, on average, are not extreme. Optically selected samples of interacting galaxies show star formation rates elevated only by factors of a few over normal galaxies, with inferred starburst mass fractions of only a few percent (e.g., Larson & Tinsley 1978; Kennicutt et al. 1987). This enhanced SFR is preferentially found in the nuclear regions of galaxies (Keel et al. 1985; Kennicutt et al. 1987), suggesting that nuclear inflow is the preferred method for triggering starbursts in interacting systems at low redshift. The most extreme examples of merger-induced activity are found in infrared samples; indeed, the most luminous starbursts in the local universe, ultraluminous infrared galaxies (ULIRGs) with luminosities $> 10^{12} L_{\odot}$ all show evidence of being interacting systems in the final throes of merging (Sanders & Mirabel 1996). Yet it is important to realize that not all merging systems are ultraluminous – the link between mergers and luminous activity is not a simple one.

Given the wide range of star-forming properties exhibited by interacting systems, what determines how a galaxy responds to an interaction? Dynamical modeling has shown that stability of the host disk plays an essential role in the degree of star-forming response. Also shown in Figure 1 is the evolution of the gas in the prograde disk during the encounter. Two distinct phases of inflow are seen – one early, and a second late in the encounter when the galaxies ultimately merge. By decomposing the torques which drive this gas inwards, we see that they are largely gravitational in origin, and that the first phase of inflow is driven by gravitational instabilities in the host disk rather than from the passing companion. The rapid inflow shown in Figure 1 is the result of bars and strong

spiral features in the host disk; in these features, the gas tends to slightly lead the stellar component (Barnes & Hernquist 1996 [BH96]), resulting in a strong gravitational torque which drives the gas inwards. In this model, the first phase of inflow is halted by the presence of a central bulge which stabilizes the inner disk; when the galaxies then ultimately merge this stability is overwhelmed by the merger process and a second phase of inflow commences. In models without a bulge, instabilities are so strong that the gas is driven to the nucleus in a single phase at early times, while the galaxies are still well-separated.

Because nuclear gas inflows are so intimately tied to instabilities in the galactic disk, star formation in interacting galaxies should depend strongly on the stability of disks against strong perturbations. This idea has been demonstrated in a number of theoretical studies. A variety of mechanisms have been shown to suppress instabilities and slow the inflow, including the presence of a dense central bulge (MH96), a lowered disk surface density relative to the dark matter content (Mihos et al. 1997), and retrograde encounter geometries, which reduce the spin-orbit coupling driving the instability (BH96). In these cases, early inflow is suppressed in favor of milder gas compressions (and, presumably, milder star formation enhancement) throughout the disk.

2. Going to Higher Redshift

Given that the response of a galaxy to an interaction is such a strong function of its internal structure, the question of how high redshift interactions behave becomes twofold:

- How do the properties of high redshift galaxies compare to those at $z = 0$?
- How do these differences translate to differences in the collisional response?

If the structural and kinematic properties of high redshift galaxies were known, we could use simple analytic perturbation theory to begin to probe their response to interaction. Disk stability depends on a variety of properties, as illustrated by the Toomre Q and X_2 parameters for local and global (bar) instabilities:

$$Q = \frac{\sigma_r \kappa}{3.36 G \Sigma} \quad X_2 = \frac{\kappa^2 R}{4\pi G \Sigma}$$

where σ_r is the radial velocity dispersion, κ is the epicyclic frequency, Σ is the disk surface density, and R is disk radius. Stability is ensured in both cases if $Q > 1$, $X_2 > 1$ ¹ (Toomre 1964, 1981). While the linear perturbation theory behind these criteria is surely inadequate to describe the self-gravitating response to a strong encounter, it at least provides a qualitative guide for galaxy behavior: disks with a rapidly rising rotation curve (due to a kinematically hot component such as a bulge) and/or a lower surface density should be preferentially more stable systems.

Unfortunately, the structural and dynamical properties of high redshift galaxies are still poorly constrained. One reasonable presumption is that high

¹In the case of X_2 , this holds for a linearly rising rotation curve. If the rotation curve is flat, the criteria becomes $X_2 > 3$.

redshift galaxies are more gas rich. For example, in an $\Omega_M = 0.3, \Omega_\Lambda = 0.7$ cosmology, a spiral galaxy formed at $z_f = 3$ with an exponentially decaying star formation rate with decay timescale $\tau = 5$ Gyr has a gas fraction of $f_g = 0.1$ at $z = 0$ and $f_g = 0.5$ at $z = 1$. This heightened gas fraction may lead to a stronger disk-wide response to an interaction. Semianalytic models (e.g., Kauffmann 1996) have suggested that in addition to being gas rich, high redshift galaxies may lie closer to a threshold density – related to the Toomre Q parameter – for triggering star formation (see Quirk 1972; Kennicutt 1989). If high redshift galaxies are gas-rich and prone to local stabilities, interactions may drive disk gas to collapse locally, igniting intense star formation throughout the disk rather than preferentially driving nuclear starbursts.

Indeed, we may be seeing such an effect in the very knotty appearance of high redshift galaxies. The fraction of peculiar and/or interacting system rises significantly at higher redshift (e.g., Glazebrook et al. 1995; Abraham et al. 1996; Ferguson et al. 2000), and these peculiarities are often manifested as multiple high surface brightness knots distributed throughout a common envelope. With large gas mass fractions, high redshift galaxies can respond quite strongly to even relatively mild interactions which, at low redshift, incite a much more subdued response.

What about instability-driven inflows and *nuclear* starbursts – are high- z disks any more or less stable than low- z disks? Unfortunately, a robust answer to this question requires detailed knowledge of the kinematics and structural properties of high- z disks, information which is not yet available. However, a number of clues hint at answers. First, out to redshifts of $z \sim 1$ there is evidence for only mild evolution in the structural properties of luminous disk galaxies (Simard et al. 1999; Vogt 2000). At higher redshifts ($z > 1$), there is some observational evidence for a decrease in the bulge-to-disk ratio of galaxies (see, e.g., the compilation in Marleau & Simard 1998), although these studies have extremely complicated selection effects (Giavalisco et al. 1996). Nonetheless these studies are consistent with theoretical models which suggest that the bulges of luminous spirals are largely in place by a redshift of $z \sim 1$ (Kauffmann 1996; Baugh et al. 1996). At the highest redshift, little structural information can be gleaned, but evidence does exist that the galaxy populations are more compact than at low redshift (Lowenthal et al. 1997; Giavalisco et al. 1996).

So where does this leave us? Based on these arguments, a cartoon picture of interaction induced star formation might look something like this:

- $z > 1 - 2$: At high redshift, galaxies are likely to be very unstable. Their large gas fractions leave them prone to violent, local instabilities, and if bulges are not yet in place, global instabilities as well. Even mild interactions may drive intense starbursts involving a substantial fraction of the gas content of galaxies, and interactions may be responsible for some of the most luminous SCUBA sources (Blain et al. 1999; Ivison et al. 2000).
- $0.5 < z < 1$: As disks build up their bulges, they begin to stabilize against violent, global instabilities. Yet their heightened gas content leaves them still subject to fairly strong disk starbursts, as evidenced by their knotty appearance. Nonetheless, the absolute star formation rates are not extreme; studies of galaxies at moderate redshifts indicate typical SFR en-

hancements of a factor of a few (Le Fevre et al. 2000), similar to that observed locally (Kennicutt et al. 1987).

- $z < 0.5$: At lower redshift, as gas reservoirs are depleted, galaxies evolve toward more quiescent interactions. This is reflected in the modest SFR enhancements of low redshift interactions (Kennicutt et al. 1987), although the ULIRG samples demonstrate that if the encounter leads to a merger, intense starbursts ensue (Sanders & Mirabel 1996).

Having made this cartoon scenario, it is now time to rip it apart – unfortunately, the situation is nowhere near as simple as spelled out above. Stability is not simply a function of bulge-to-disk ratio, but depends rather on the mass distribution and kinematics of galaxies. Compare for example the models of MH96 with those of BH96, both of which used galaxies with $B/D=1/3$, but with differing bulge densities. In the MH96 models, the inflow response was rather insensitive to orbital geometry, as the presence or absence of a dense bulge dominated the dynamics of the inner few kpc of the galaxies. In contrast, the more diffuse bulges of BH96 provided comparatively less stability, so that the disks were more vulnerable to interaction driven instabilities. This uncertainty is reflected in the fact that there is a very large scatter in star forming properties along the Hubble sequence and that star formation appears more closely tied to global gas content than bulge-to-disk ratio (Kennicutt 1998). Indeed the crucial information needed to understand the stability properties of high redshift disks is high quality, spatially resolved kinematic and structural data on galaxies as a function of redshift.

Other questions abound as well. How are bulge and disk formation linked? If bulges form first, and disks grow around them through gas accretion into the potential well, the disks should begin life globally stable, and move towards instability as the disk surface density increases. Also, what role does secular evolution play in the formation of bulges? Models of disk galaxy evolution have suggested that some bulges form as a result of instabilities in the stellar disk (e.g., Pfenniger & Norman 1990; Norman et al. 1996; Corteau et al. 1996). Under these models, disks form first, while bulges build up continuously over cosmic time, so that the disk galaxy population as a whole may gradually become *more* stable against strong inflow and starbursts. Unfortunately, the stabilizing properties of these “secular” bulges is unclear — growing from material originally in the disk, these bulges may have a faster rotation than true $r^{1/4}$ bulges (Kormendy 1993) and may not provide strong dynamical stability.

3. Cluster Environments

The fact that our knowledge of interactions comes largely from the local universe also means that we are largely observing interactions between field galaxies, or galaxies within evolved clusters. When looking at galaxy clusters at higher redshift, we see clusters which are dynamically young, and galaxies which may be falling into clusters for the first time. A variety of dynamical mechanisms operate on galaxies within clusters: *cluster tides* act to strip the outer regions of cluster galaxies (e.g., Malamuth & Richstone 1984), and drive instabilities in infalling disks (Byrd & Valtonen 1990); *collisions and mergers* of galaxies in the

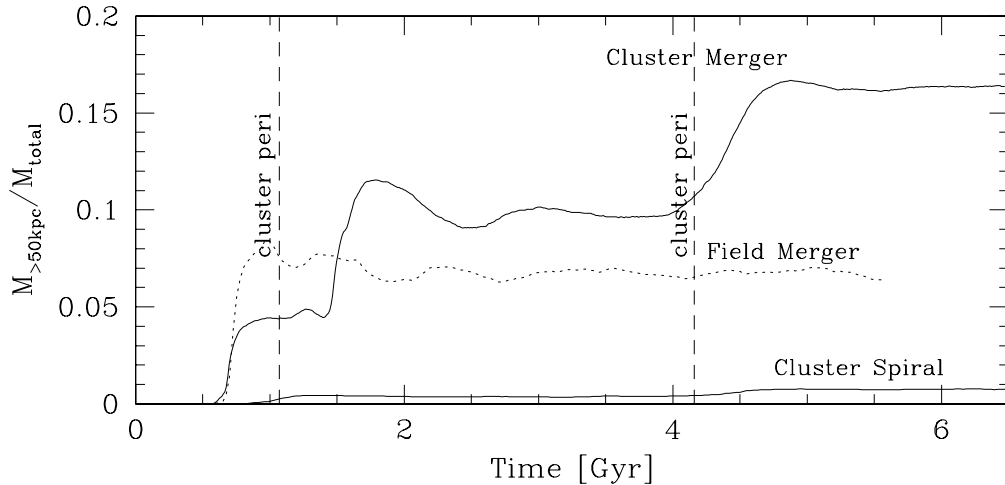


Figure 2. The evolution of tidally stripped material (defined as the fraction of disk material at radius $r > 50$ pc) in different environments. The “field merger” curve shows the fraction of material lost from a major merger of two spiral galaxies in the field environment (see Figure 1). The “cluster merger” curve shows the same merger, but this time occurring in a Coma-like cluster potential (Geller et al. 1999). In this potential, the galaxy pair orbits with $r_{peri} = 0.5$ Mpc and $r_{apo} = 2.0$ Mpc. The “cluster spiral” curve shows stripping from a single non-interacting spiral galaxy on the same cluster orbit.

high density environment drive evolution in the galaxy populations; *high speed encounters* between galaxies in clusters impulsively heat galaxies (e.g., Moore et al. 1996); and *ram pressure stripping* may compress and remove the ISM from infalling disks, first igniting a starburst, then rapidly shutting it down (Gunn & Gott 1972).

Before addressing how cluster interactions evolve in detail, we should ask, given the high velocity dispersions of clusters, so we expect any slow collisions or mergers at all? Certainly an individual galaxy traveling at high speed through the cluster potential will have little chance of a slow interaction with another cluster member. However, clusters grow hierarchically, by accreting small groups of galaxies, and interactions within the infalling groups may occur before the group is disrupted by the tidal field of the cluster. N-body simulations of the formation of rich clusters shows clearly that this process occurs (e.g., Dubinski 1998), and we see evidence for slow interactions in clusters at moderate redshift (Couch et al. 1998; van Dokkum et al. 2000). The rate of accretion onto clusters is a strong function of redshift and cosmology; simulations by Gighna et al. (1998) suggest that mergers within the cluster virial radius are largely shut off at redshifts $z < 0.5$. Unlike studies of nearby clusters, at higher redshifts slow interactions may play a very important role in the evolution of cluster galaxies.

Interactions and mergers in the cluster environment should differ from field collisions in a number of ways. Of particular interest is the role of the cluster

tides and hot ICM on the diffuse tidal material generated during a low speed collision. In the field, the overwhelming majority of the tidally liberated gas and stars in mergers remains bound to the remnant, falling back over several Gyr, and leaving a long-lived record of the interaction on the remnant (Hibbard & Mihos 1995). The continued reaccretion of gas by the remnant may result in the HI disks observed in several nearby field ellipticals, and perhaps may even result in the delayed formation of S0s (e.g., Schweizer 1998). In contrast, the cluster environment will rapidly remove this material from any merger remnant in the cluster, feeding both the hot ICM and the diffuse intracluster starlight (see Figure 2). In contrast to traditional picture of cluster tidal and ram pressure stripping – which affect primarily the outskirts of galaxies – cluster interactions and mergers act to accentuate the process by “dredging up” material from the inner regions of galaxies and moving it to large radius, where the cluster tides and (in the case of tidally liberated HI) hot gas can efficiently strip it. In the context of S0 formation models, delayed formation of S0s through reaccretion of tidal gas seems not to be a viable option in the cluster environment. However, the disk heating associated with galaxy interactions (e.g., Walker et al. 1996) could still lead to the formation of disk S0s in clusters.

Finally, the role of ram pressure stripping (RPS) in driving galaxy evolution remains unclear. Several authors have invoked RPS as a way of truncating star formation and forming E+A and S0 galaxies in clusters. However, RPS affects predominantly the outer HI disks of galaxies, and should leave the inner molecular gas intact. Indeed, recent RPS simulations by Quilis et al. (2000) only succeeded in removing the ISM of cluster galaxies in models where the gas distribution in the disk had a central hole; these authors posit that the central molecular gas would rapidly dissociate due to a triggered starburst, and be swept from the disk over very short timescales ($\Delta t \sim 10^7$ years). However, from an observational standpoint, this appears not to be the case. The molecular gas in cluster galaxies seems to survive the cluster environment: Kenney & Young (1989) find that HI deficient Virgo spirals contain significant quantities of molecular gas, while Casoli et al. (1998) find no CO deficiency in cluster spirals. Interestingly, there is evidence that some poststarburst galaxies in clusters may still have appreciable obscured star formation (Smail et al. 1999), arguing that star formation in cluster spirals is extended in duration ($\Delta t \sim \text{several} \times 10^8 - 10^9$ years). Given the fact that cluster interactions and mergers occur, and that cluster galaxies can retain some fraction of their gas for an appreciable time, it seems premature to abandon collisional formation mechanisms for the formation of some cluster E+A and S0 galaxies at higher redshift.

This research is sponsored in part by an NSF Career Fellowship and the San Diego Supercomputing Center.

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